EUROTeV-Report-2006-004

Ion Effects in the Damping Rings for ILC --- An Introduction

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May 15, 2006

Abstract

An introduction of ion effects in the damping rings are presented in this paper. Firstly, the theory of conventional ion trapping effect is briefly reviewed. Then, the so called fast beam-ion instability (FBII) is introduced and its impact on the damping ring of the International Linear Collider (ILC) is analyzed. Finally, the growth time of FBII is analytically calculated in different sections for OCS and TESLA damping rings, respectively.

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1 Introduction

Ionisation of residual gases in the vacuum chamber of an accelerator will create positively charged ions. Under certain circumstances these ions can be trapped in the potential well of circulating electron bunches. Circulating positron bunches do not trap ions. The accumulation of these trapped ions is in general detrimental to the performance of the storage rings. It will lead to beam size blow-up, tune shifts, tune spreads and emittance blow-up etc. The comparison of simulation results with experiment is very difficult, and observational evidence can be difficult to reproduce. However, a linear theory can give an approximate prediction of these ion effects.

The mechanism of ion trapping can be understood by considering that the circulating electron bunches act as focusing elements on the residual gas ions, acting on them in a manner analogous to the effect of quadrupole on the electron bunches. Stability criteria for ion trapping can then be derived in a similar way as the formalism used in accelerator optics.

In this paper, the linear theory of ion trapping is firstly introduced in section 2. The stability condition of ion motion is given too. For the low-emittance, high bunch charge machines like damping rings of ILC, the single passage ion effect, namely, fast beam-ion instability (FBII) is predominant. Then in the section 3, the FBII is devoted to emphasize. By using the linear theory, the growth time due to FBII is analytically estimated in different sections of OCS and TESLA damping rings. Finally, the conclusion and outlooks are given.

2 Theory of Ion Trapping

2.1 Linear Theory for Homogenous Bunches

The residual gas ionized ions will experience a force from a passing electron bunch, which can be regarded as a thin lens focusing element followed by a drift space before the next bunch passes. A transport matrix for this cell can be defined as [1]

$$\begin{pmatrix} u \\ \dot{u} \end{pmatrix}_1 = \mathbf{M} \cdot \begin{pmatrix} u \\ \dot{u} \end{pmatrix}_0 = \begin{pmatrix} 1 & t_b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -a_u & 1 \end{pmatrix} \begin{pmatrix} u \\ \dot{u} \end{pmatrix}_0 \tag{1}$$

where u refers to general transverse coordinates, $\dot{u}$ is its time derivative, t_b is the drift time between adjacent bunches. a_u is a linear kick parameter, which for a particular atomic weight A of ions is given by

$$a_u = \frac{2N_b r_p c}{A\sigma_y\left(\sigma_x + \sigma_y\right)} \tag{2}$$

where N_b is the number of particles in the bunch, r_p is the classical proton radius, σ_x, σ_y are the horizontal and vertical beam sizes, respectively, c is the speed of light.

If the bunches are equally spaced, namely, for the homogenous bunches distribution, the stability criterion for stable focusing is given by

$$\left|Tr\mathbf{M}\right| < 2 \tag{3}$$

For a particular electron density this leads to a critical mass and above which ions are trapped in a storage ring. It is given by

$$A_c > \frac{CNr_p}{2n^2\sigma_y(\sigma_x+\sigma_y)} = \frac{N_b r_p L_{sep}}{2\sigma_{x,y}(\sigma_x+\sigma_y)} \tag{4}$$

where N is the total number of particles in the beam, n is the number of circulating bunches, and C is the ring circumference, L_{sep} is the bunch spacing in meter.

2.2 Stability of Ion Motion in the Damping Ring

For the damping rings of ILC, the bunch trains are injected with equal spacing. Hence, the above mentioned matrix can be extended to the case where there are gaps in the bunch train. For the gapped trains in a damping ring, the transport matrix for a complete bunch train becomes

$$\mathbf{M} = \left[\begin{pmatrix}1 & t_b\\0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\-a_u & 1\end{pmatrix}\right]^n \begin{pmatrix}1 & t_b\\0 & 1\end{pmatrix}^{[h-n]} \tag{5}$$

where n is the number of bunch in the train, h is the harmonic number of the damping ring (i.e. the total number of bunches). The same stability criterion given by equation (3) still applies, and can be readily evaluated for particular conditions.

From equation (2) we can see that the interaction force (attractive force) from the ions is closely related to the beam sizes. In order to study the ion effects in the damping ring, we should notice that the beam sizes vary along the ring lattice. At a certain location of the damping ring, the transverse beam sizes are calculated by

$$\sigma_x(t) = \sqrt{\varepsilon_x(t)\beta_x + \eta_x^2\sigma_\delta^2(t)} \tag{6}$$

$$\sigma_y(t) = \sqrt{\varepsilon_y(t)\beta_y + \eta_y^2\sigma_\delta^2(t)} \tag{7}$$

where $\beta_{x,y}$ and $\eta_{x,y}$ are the betatron and dispersion functions, σ_δ is the rms energy spread. In general case, $\eta_y \approx 0$, hence the vertical beam size is $\sigma_y(t) = \sqrt{\varepsilon_y(t)\beta_y}$.

During damping process, the beam emittances are different from time to time. Therefore, the beam emittance is different for different bunch trains, which can be seen from Fig.1. For the sake of simplicity, we assume that the transverse and longitudinal distributions in a bunch are always Gaussian, and then the beam emittances and rms energy spread are described as [2]

$$\varepsilon_x(t) = \varepsilon_{x,0}e^{-2t/\tau_x} + \left(1-e^{-2t/\tau_x}\right)\varepsilon_{x,\infty} \tag{8}$$

$$\varepsilon_y(t) = \varepsilon_{y,0}e^{-2t/\tau_y} + \left(1-e^{-2t/\tau_y}\right)\varepsilon_{y,\infty} \tag{9}$$

$$\sigma_\delta(t) = \sigma_{\delta,0}e^{-t/\tau_\delta} + \left(1-e^{-t/\tau_\delta}\right)\sigma_{\delta,\infty} \tag{10}$$

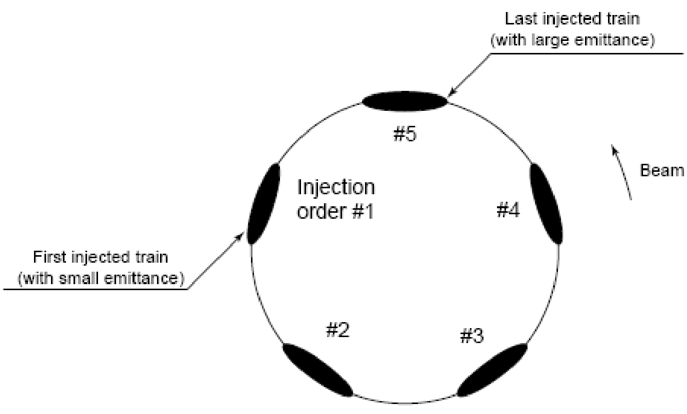

Fig. 1 Beam filling in the damping ring, 5 bunch trains are depicted. Each bunch train has a different time after injection and thus different emittance

where t is the time after the bunch is injected; $\tau_x, \tau_y, \tau_\delta$ are the transverse and longitudinal damping times. $\varepsilon_x(t), \varepsilon_y(t)$ are the horizontal and vertical emittance respectively $\varepsilon_{x,0}, \varepsilon_{y,0}$ are the initial horizontal and vertical emittance, $\varepsilon_{x,\infty}(t), \varepsilon_{y,\infty}(t)$ are the equilibrium horizontal and vertical emittance, σ_δ is the rms energy spread, $\sigma_{\delta,0}, \sigma_{\delta,\infty}$ are the initial and equilibrium energy spread, respectively. We assume the initial emittance is 45μm and the equilibrium emittances are 5μm and 0.02μm in horizontal and vertical plane, respectively. Fig.2 and Fig.3 depict the variation of beam emittance with respect to the damping times.

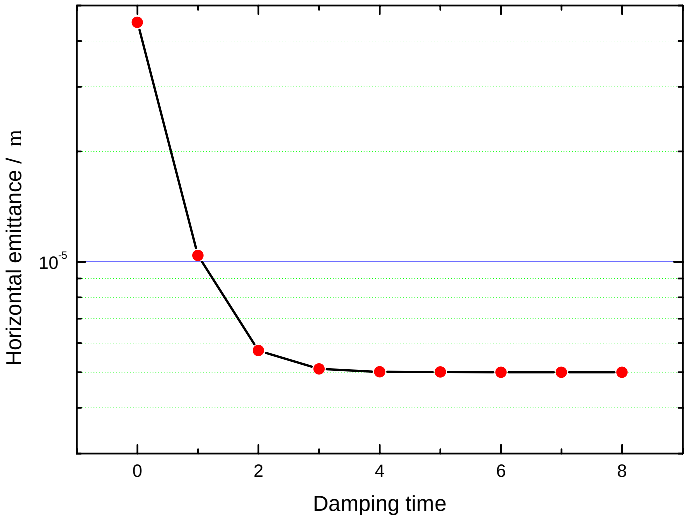

Fig.2 The horizontal emittance variation *vs*. damping time

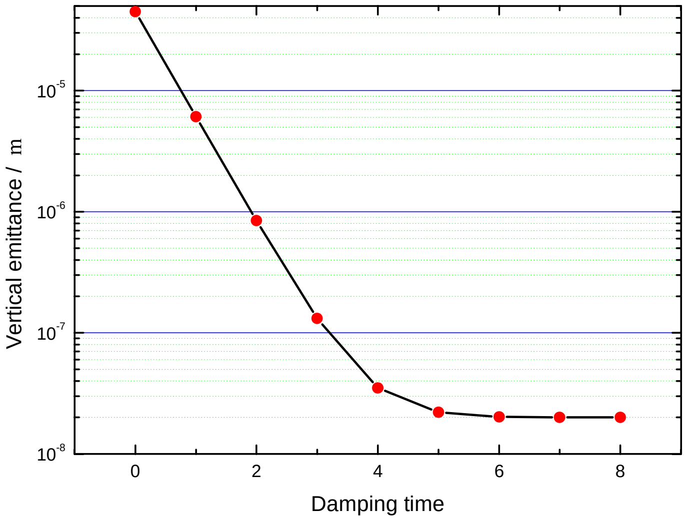

Fig.3 The vertical emittance variation *vs*. damping time

(Here we assume the initial emittance is 45μm and the equilibrium emittances are 5μm and 0.02μm in horizontal and vertical direction, respectively. This data coincide with the data in draft report of ILC damping ring baseline recommendation)

For the TESLA damping ring, as we known, the total 2820 bunches fill in the whole ring uniformly (only one train in the ring). The length of a bunch is 6mm, while the spacing between two adjacent bunches is 6m (20ns). Because 6mm << 6m, then the attractive force ions feel from the beam bunches can be dealt with thin lens model. We can use the conventional ion trapping theory to clarify the case in TESLA damping ring.

If we use the TESLA damping ring parameters (coupling bumps in the long straight are used) [3], we can find the critical mass in the long straight section is 1 (a large margin to trap other ions like CO^+ and CO_2^+). It means every ion species will be trapped in the potential well of beam bunches.

It is also noted that in the vacuum chamber, the main composition of residual gases are H_2 and CO (vacuum chamber is backed and after conditioning), due to the differences of collision ionization cross section, (at beam energy of 5GeV, the collision ionization cross section of H_2 is $3.1\times10^{-23}\text{m}^2$, while for the CO, the value is $1.9\times10^{-22}\ \text{m}^2$, so the value of ionization cross sections for CO is a factor of 6~7 larger than that of H_2)[4]. Therefore, we think the dominant ions are CO^+ in the vacuum chamber, which is coincide with the measurement of KEK PF [5].

In addition, there is a criterion on trapping condition. In other words, if the transverse velocity of ions is so small that they stay within the bunch size before the next bunch arrives which pulls them back in, the trapping condition is then fulfilled. This condition can be expressed in a transverse frequency f_i which has to be smaller than the bunch repetition frequency, namely

$$4f_i \le \frac{c}{L_{sep}} \tag{11}$$

where the ion oscillation frequency f_i is given by

$$f_i = \frac{1}{2\pi}\left(\frac{4N_b r_p c^2}{3AL_{sep}\sigma_y\left(\sigma_x+\sigma_y\right)}\right)^{1/2} \tag{12}$$

Using TESLA damping ring parameters listed in Table 1, we can get the results as following: $4f_i = 1.36\times10^{-7}\text{s}^{-1}$, while $c/L_{sep}=5.0\times10^{-7}\text{s}^{-1}$. Therefore we draw the conclusion that the ion like CO^+ will be trapped in the potential well of beam bunches.

3 Fast Beam-Ion Instability

For future accelerators operating in a new regime with the high current long bunch train and very small transverse beam emittance, the ions generated within a single bunch train can have significant effects; the same is true in transport line and linacs, where the vacuum pressure is relatively high. The growth time of this effect is too quick to be cured by present feedback systems. So this single passage ion effect is called "fast beam-ion instability" (FBII). The analytic theory of FBII was first proposed by Tor Raubenheimer and Frank Zimmermann [6,7], and has been observed in some experiments [8-11]. The ion line density at the end of the bunch train is given as

$$\lambda_{ion} = \sigma_{ion} n_b N_b p / k_b T \tag{13}$$

where σ_{ion} is the ionization cross section, n_b is the bunch number, N_b is the number of particles per bunch, p is the partial residual gas pressure which leads to instability, k_b is the Boltzmann Constant, T is the gas temperature. The collected ions will also lead to an incoherent tune shifts, which may estimated as follows [12]

$$\Delta Q_y = \frac{1}{4\pi}\oint_C \beta_y K_y^{ion} ds \approx \frac{\lambda_{ion} r_e C}{\pi\sqrt{\gamma\varepsilon_x \gamma\varepsilon_y}} \tag{14}$$

where, C is the circumference of machine, $\gamma\varepsilon_x, \gamma\varepsilon_y$ are the normalized horizontal and vertical emittance of beam. Using the parameters of OCS and TESLA damping rings in Table 1 [3], the ion line density and tune shifts at the bunch train end due to ions are listed in Table 2.

From Table 2, we can see that the tune shift due to ions is quite large at 1 nTorr, so the lower vacuum gas pressure (lower than the nominal gas pressure) is critical to alleviate the ion effects in the damping ring. The ion line density and tune shifts with respect to gas pressure in

OCS and TESLA damping rings are depicted as Fig.4 and Fig.5, respectively.

Table 1 Parameters of the ILC damping rings

ring	ILC OCS arc	ILC OCS wiggler	ILC OCS str.	ILC TESLA arc	ILC TESLA wiggler	ILC TESLA str.
circumference [km]	6,1			17		
length [km]	3	0,12	3	2,0	0,54	14,5
energy [GeV]	5			5		
no. of bunches	2820			2820		
bunch population	2×10^{10}			2×10^{10}		
bunch separation [m]	1,844			5,994		
norm.hor. emittance $\gamma\varepsilon_x$ [μm]	5,5			5		
norm.vert. emittance $\gamma\varepsilon_y$ [μm]	0,02			0,014		
average hor. β function β_x [m]	26	15,7	29,3	11,9	10,2	139
average vert. β function β_y [m]	32,5	9,2	39	24,8	13,5	142
average hor. beam size σ_x [mm]	0,618	0,094	0,128	0,357	0,072	0,267
average vert. beam size σ_y [mm]	0,008	0,004	0,009	0,06	0,004	0,014

Table 2 The ion line density and tune shifts due to ions

Gas pressure [nTorr]	0,01	0,1	1
Line density of ions at train end [m^{-1}]	3630,8	36308,1	363081,0
Incoherent tune shift at train end for OCS	0,0600	0,600	6,004
Incoherent tune shift at train end for TESLA	0,209	2,093	20,925

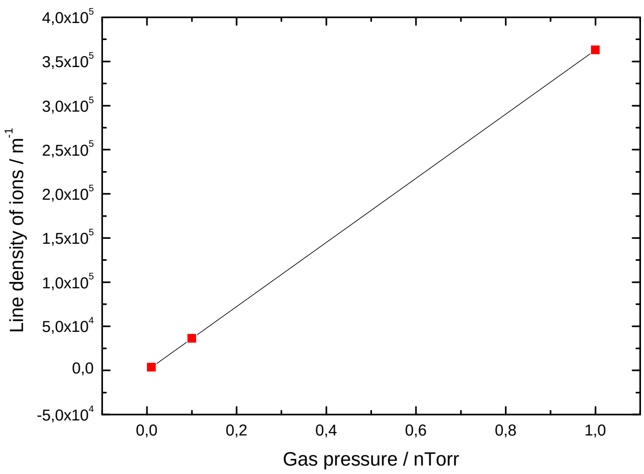

Fig. 4 The line density of ions *vs.* the gas pressure in the ILC OCS damping ring

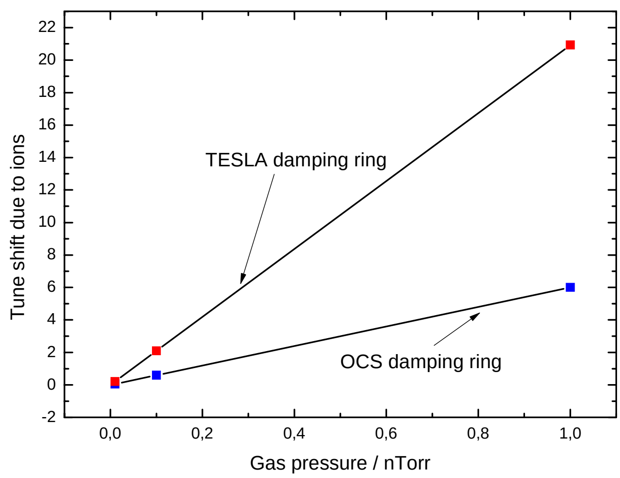

Fig. 5 The tune shift due to ions *vs.* gas pressure in OCS and TESLA damping ring

According to linear theory, the growth rate of FBII strongly depends on the number of bunches, the transverse beam sizes and the residual gas pressure. According to the linear theory, the vertical action of the final bunch in the train grows as follows

$$J_y = \frac{J_{y0}}{8\pi\sqrt{t/\tau}} \exp\left(2\sqrt{\frac{t}{\tau}}\right) \tag{15}$$

in which the growth time τ is given as

$$\tau^{-1}(s^{-1}) = 5p[Torr]\frac{N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma \sigma_y^{3/2} \left(\sigma_x + \sigma_y\right)^{3/2} A^{1/2} \omega_\beta} \tag{16}$$

where r_p and r_e are the classical radius of proton and electron respectively, L_{sep} the bunch spacing, c the speed of light, A the atomic mass number of the residual gas molecules leading to the instability, $\omega_\beta \approx 1/\beta_y$. We had assumed an ionization cross section of 2Mb. If the oscillation arises from Schottky noise, the initial vertical action may be estimated as [13]

$$J_{y0} \approx \frac{\sigma_y^2}{2N_b n_b \beta_y} \tag{17}$$

The growth time predicted from this theory for the OCS and TESLA damping rings are shown as a function of gas pressure in Fig.6. Here, we do not consider the gaps for the OCS bunch trains and we assume the residual gas as CO (A=28).

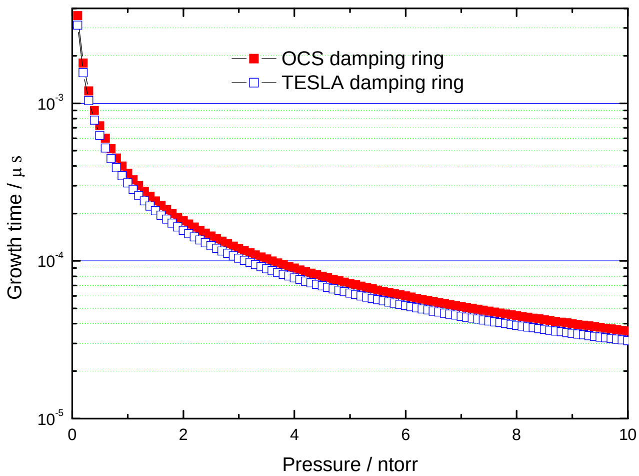

Fig.6 Fast beam-ion instability growth time as a function of vacuum pressure

From Fig.6 we can see that the growth time of FBII varies greatly with respect to the gas pressure for both the OCS and TESLA damping rings. Therefore, a good vacuum pressure is critical for ion effects. Fig.7 shows the vertical action of the final bunch in the train for the TESLA damping ring. The parameters we used are listed in Table 1. We cans see that the beam vertical action increases along the damping time (here we assume 2 times of damping time). In addition, for the partial gas pressure CO^+ of 1ntorr, the vertical action of the final bunch in the train is greatly larger than that of 0,1ntorr.

The growth time of FBII can be calculated analytically. By using the parameters of OCS and TESLA damping rings, the growth time variation with respect to the bunch number in the different sections, i.e. straight section, arc section and wiggler section are respectively depicted from Fig.6 to Fig.17, in which the hollow squared points denote 10% of ion frequency spread along the ring and the solid squared points denote the growth time without the ion frequency spread. We use the average beam transverse sizes as constant in calculation.

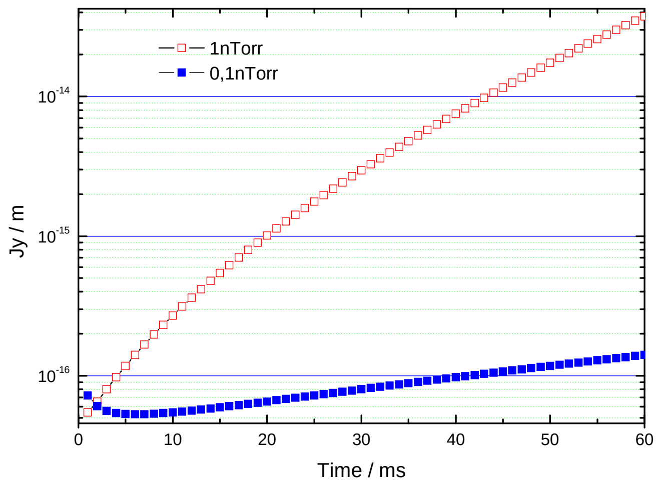

Fig.7 The action of vertical betatron amplitude *vs.* damping time
(We assume twice of damping time of TESLA damping ring)

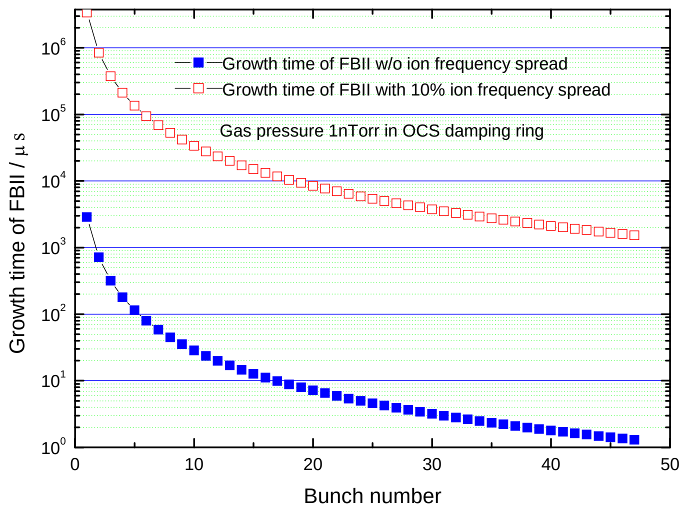

Fig. 8 Growth time of FBII in straight section of OCS damping ring in 1nTorr

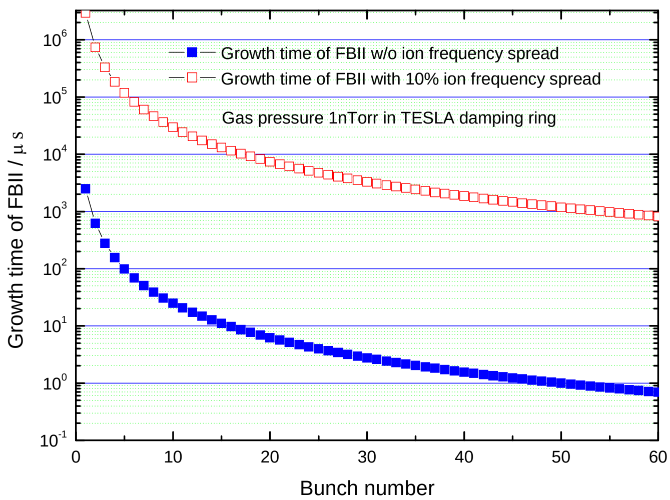

Fig. 9 Growth time of FBII in straight section of TESLA damping ring in 1nTorr

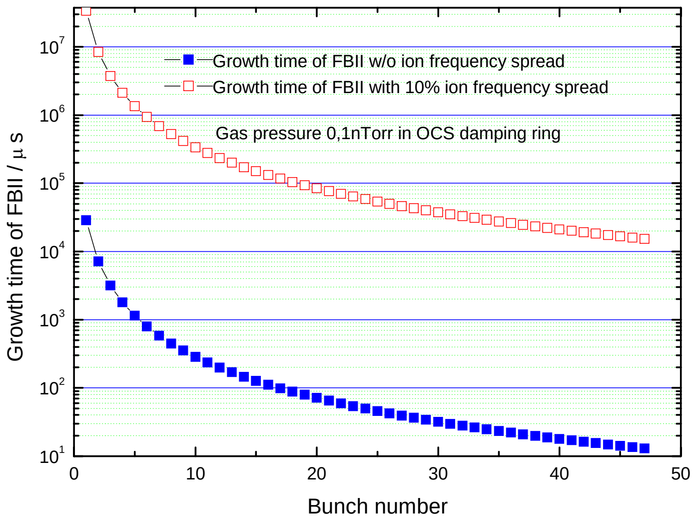

Fig. 10 Growth time of FBII in straight section of OCS damping ring in 0,1nTorr

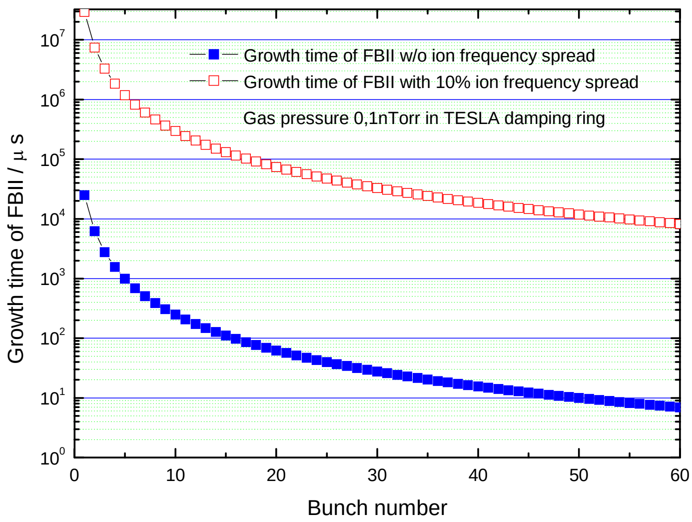

Fig.11 Growth time of FBII in straight section of TESLA damping ring in 0,1nTorr

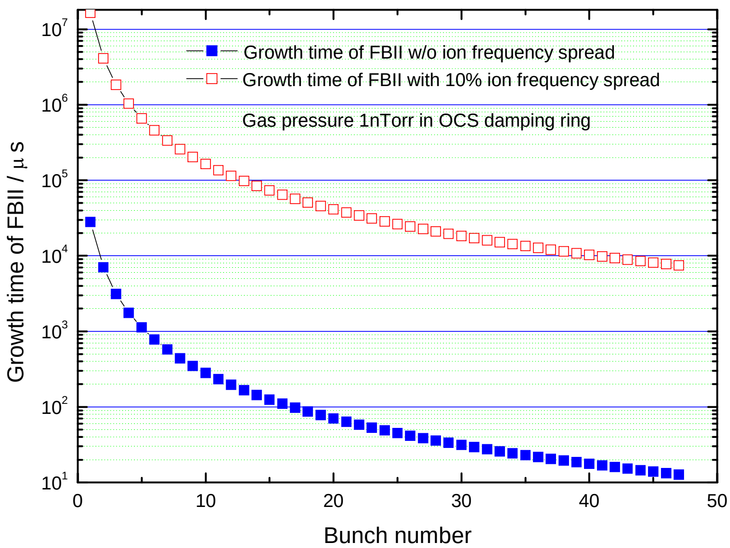

Fig.12 Growth time of FBII in arc section of OCS damping ring in 1nTorr

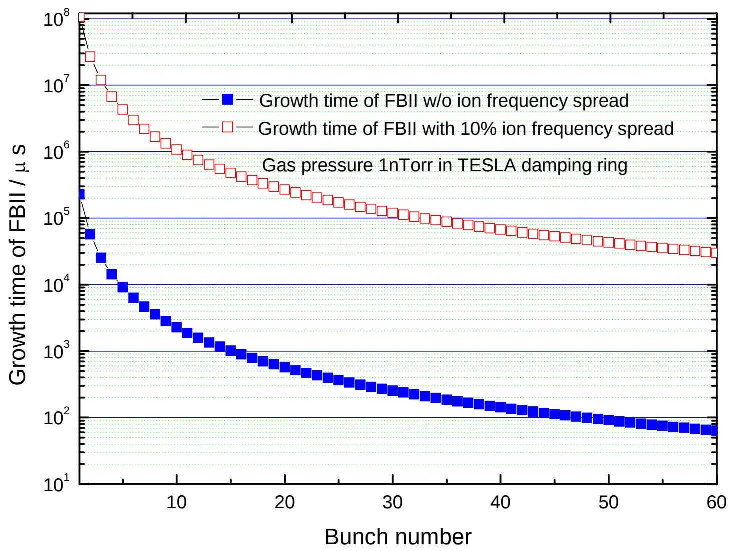

Fig. 13 Growth time of FBII in arc section of TESLA damping ring in 1nTorr

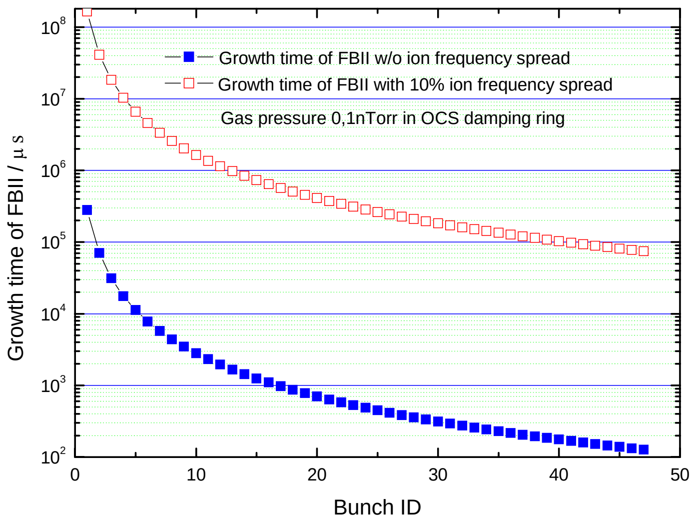

Fig. 14 Growth time of FBII in arc section of OCS damping ring in 0,1nTorr

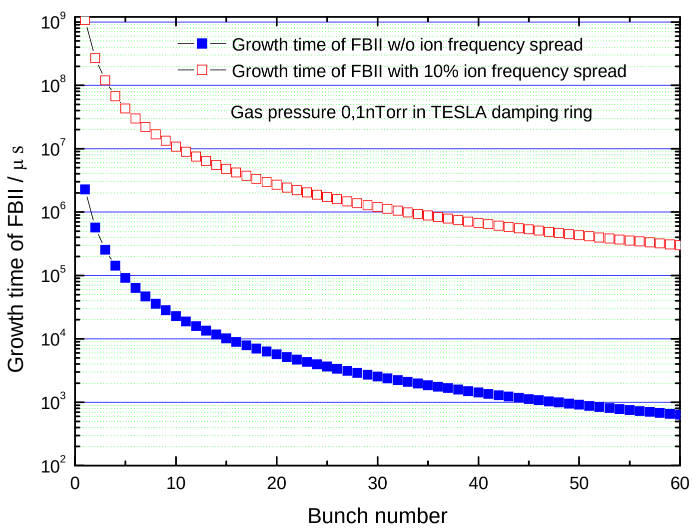

Fig.15 Growth time of FBII in arc section of TESLA damping ring in 0,1nTorr

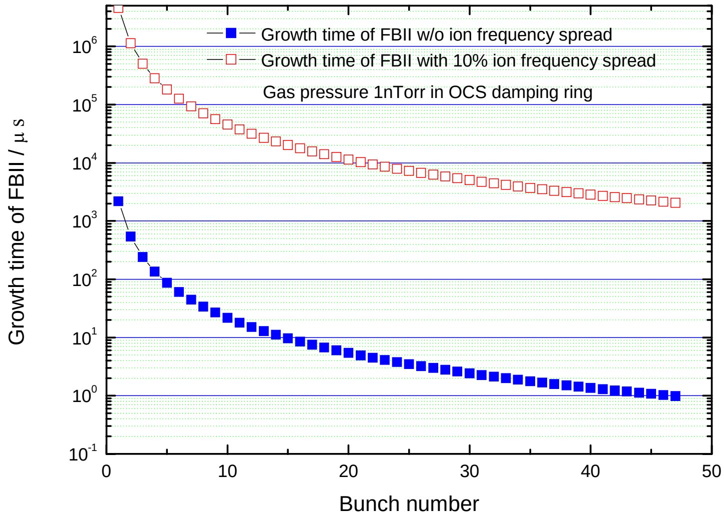

Fig.16 Growth time of FBII in wiggler section of OCS damping ring in 1nTorr

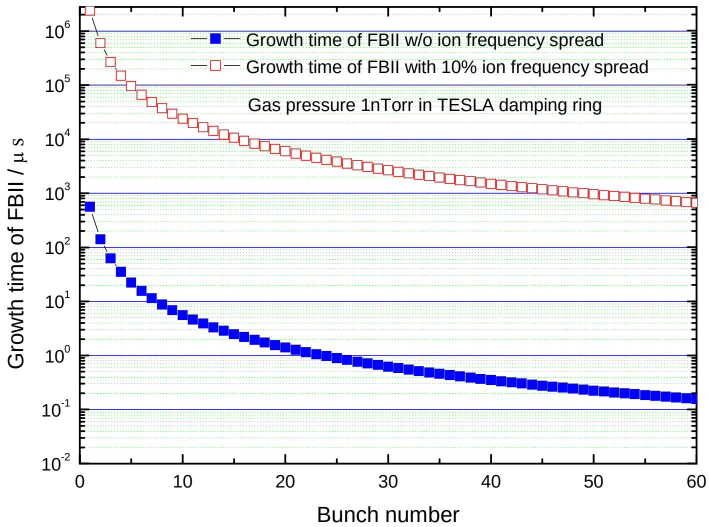

Fig. 17 Growth time of FBII in wiggler section of TESLA damping ring in 1nTorr

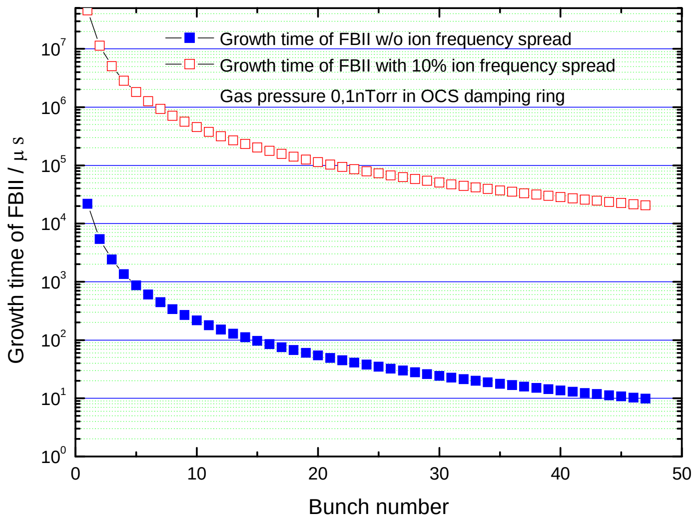

Fig. 18 Growth time of FBII in wiggler section of OCS damping ring in 0,1nTorr

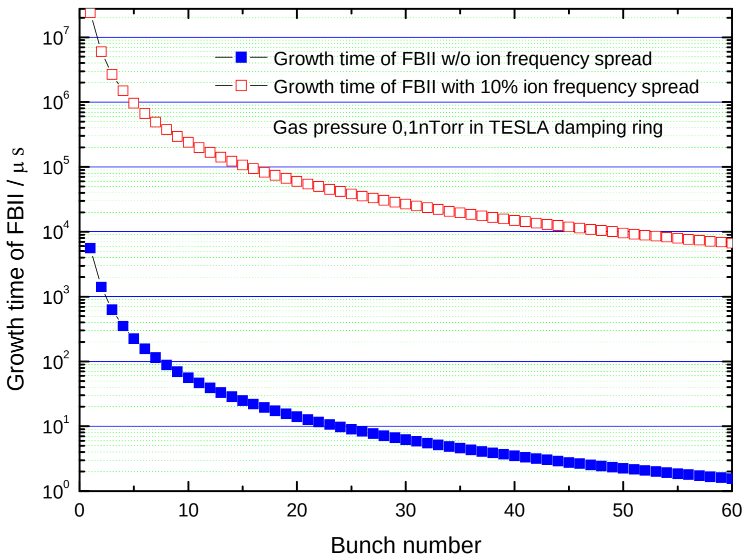

Fig. 19 Growth time of FBII in wiggler section of TESLA damping ring in 0,1nTorr

The above figures (from Fig.8 to Fig.19) denote the growth time variation with respect to the number of bunches. We take the vacuum pressure as 1,0nTorr and 0,1nTorr respectively, which is also attainable for current vacuum technology in the case of good conditioning of vacuum chamber materials. We calculated the growth time variation in different sections, namely, long straight section, arc section and wiggler section, respectively. The parameters of the damping rings are from Table 1, which is the same as the Table 5 from Frank Zimmermann's paper, ILC-Asia-2005-24 [3].

From the analytical results, one can see that the growth time becomes strikingly longer if 10 percent of the ion frequency spread is taken into account. By comparison with the calculated results from Table 3 (here we take the bunch index of 10 as an example), we found that the growth time with 10% ion frequency spread is about 1000 times larger than that of without ion frequency spread. In addition, the growth time in different section is quite different. The growth time in the wiggler section is smaller compared to the long straight section and arc section, both for OCS and TESLA damping rings. This is partly due to the small beam sizes in the wiggler section.

Table 3 Comparison of growth time of FBII for different bunch index

	OCS damping ring (1nTorr)			TESLA damping ring (1nTorr)		
Bunch index	straight	arc	wiggler	straight	arc	wiggler
1	2860(3,3E6)	28094(1,6E7)	2173(4,5E6)	2483(2,9E6)	228035(1,0E8)	561(2,4E6)
2	715(843231)	7023(4,1E6)	543(1,1E6)	620(738914)	57008(2,6E7)	140(600603)
3	317(374769)	3121(1,8E6)	241(505084)	275(328406)	25337(1,1E7)	62(266935)
4	178(210807)	1755(1,0E6)	135(284110)	155(184728)	14252(6,7E6)	35(150150)
5	114(134917)	1123(657580)	86(181830)	99(118226)	9121(4,3E6)	22(96096)
6	79 (93692)	780(456653)	60(126271)	68(82101)	6334(2,9E6)	15(66733)
7	58 (68835)	573(335500)	44(92770)	50(60319)	4653(2,1E6)	11(49028)
8	44 (52701)	438 (256867)	33(71027)	38(46182)	3563(1,6E6)	8(37537)
9	35 (41641)	346(202957)	26(56120)	30(36489)	2815(1,3E6)	6(29659)
10	28 (33729)	280(164395)	21(45457)	24(29556)	2280(1,0E6)	5(24024)

Conclusion and outlooks

In an electron storage ring, when the ions are trapped in the potential well of beam bunches, although the ions are stable, the two-stream instabilities come up [14]. A series of negative effects will happen to the circulating beam due to ions. These effects include beam lifetime reduction [15], vertical beam size blow up [16], the transverse emittance growth [17], tune shift and tune spread [18], transverse beam coupling instabilities [19,20] etc.

When the ion trapping happens, these ions will disturb the motion of beam bunches. Generally, in order to avoid the conventional ion trapping, the simplest method is to leave a gap in the bunch train (leave some RF buckets empty and the length of gap corresponding to a few percent of the ring circumference). Besides, some other remedies can also be used to alleviate the ions effects including usage of static clearing electrodes, clearing electrodes with an oscillation field at ion oscillation frequency and beam shaking techniques (frequency modulation of the beam) etc. However, the most critical solution is vacuum system improvement because collision ionization with the residual gas is the main source of ions production.

Although some experiments can give us some concepts about the FBII [8-11], there is no a machine like ILC damping ring with such a low emittance (nominal normalized vertical emittance of 20nm) and high bunch charge (2×10^{10} particles per bunch). Although KEK ATF claimed they achieved the most minimum emittance in the world, 4.5pm @ 1.28GeV, which is still a factor of 2~3 lower than that of ILC damping ring. Also the energy of ATF is a factor of 4 less than that of damping ring for ILC, In addition, there is less bunch charge in ATF damping ring [21]. Anyway, ATF is still a good prototype machine to test the beam dynamics due to IBS, FBII, ecloud etc which we concern very much [22].

Therefore, a lot of work should be done further on R&D of damping rings, especially for fast beam-ion instability.

Acknowledgement

This work is supported by the Commission of the European Communities under the 6th Framework Programme "Structuring the European Research Area", contract number RIDS-011899.

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